Universality of the Small-Scale Dynamo Mechanism

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"Is the solar convective velocity field capable of supporting classical turbulent small-scale dynamo action?" We determine if the dynamo in realistic simulations of solar surface convection is the same as in idealistic simulations by measuring the wavelength-dependent energy transfer rates.

We compare the dynamo generation of magnetic field in three incrementally more realistic simulations in both the initial (kinematic) and saturated states.

- Isotropic, homogeneous, incompressible turbulence (HoT)
- Boussinesq convection
- MURaM: realistic solar magnetoconvection code (Vögler et al. 2005) including
  - Strong stratification
  - Full compressibility
  - Partial ionization
  - Radiative transfer

Methods

Transfer functions (below) measure the conversion of kinetic energy to magnetic energy through the magnetic tension force: $T_{BV}(q)<0$ measures kinetic energy lost from wavenumber q doing work against the magnetic tension force at all wavenumbers; $T_{VB}(k)>0$ measures the magnetic energy generated at wavenumber k by stretching of field lines by all wavenumbers of fluid motions.

$$\hat{\vec{v}}^* \cdot F[\partial_t \hat{\vec{v}} + \overbrace{\vec{v}\cdot\nabla\vec{v} + \nabla(P+\frac{1}{2}|B|^2)}^{T_{VV}(q)}] = \overbrace{\vec{B}\cdot\nabla\vec{B}}^{T_{BV}(q)} + \overbrace{\nu\nabla^2\vec{v}}^{D_\nu(q)}]$$

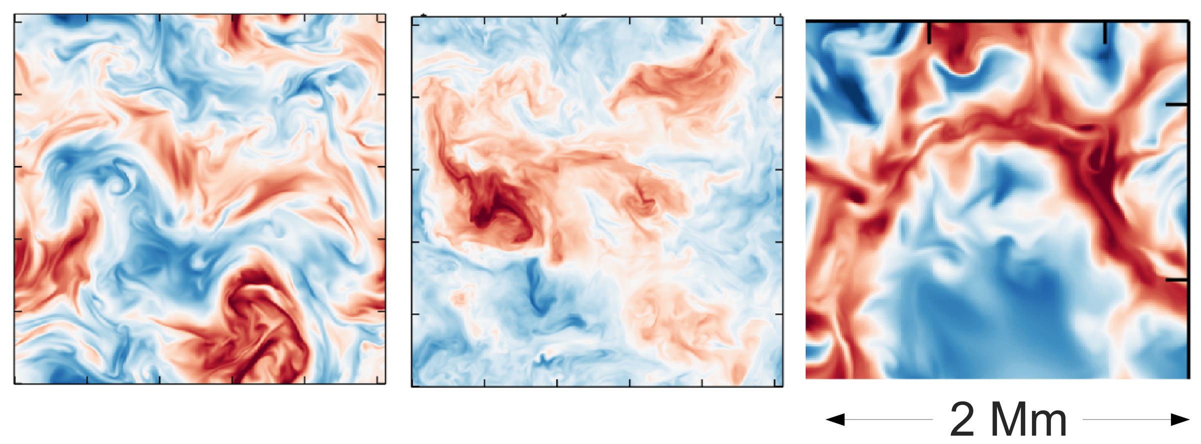
$$\Updownarrow$$

$$\hat{\vec{B}}^* \cdot F[\partial_t \hat{\vec{B}} + \underbrace{\vec{v}\cdot\nabla\vec{B}}_{T_{BB}(k)}] = \underbrace{\vec{B}\cdot\nabla\vec{v}}_{T_{VB}(k)} + \underbrace{\eta\nabla^2\vec{B}}_{D_\eta(k)}]$$

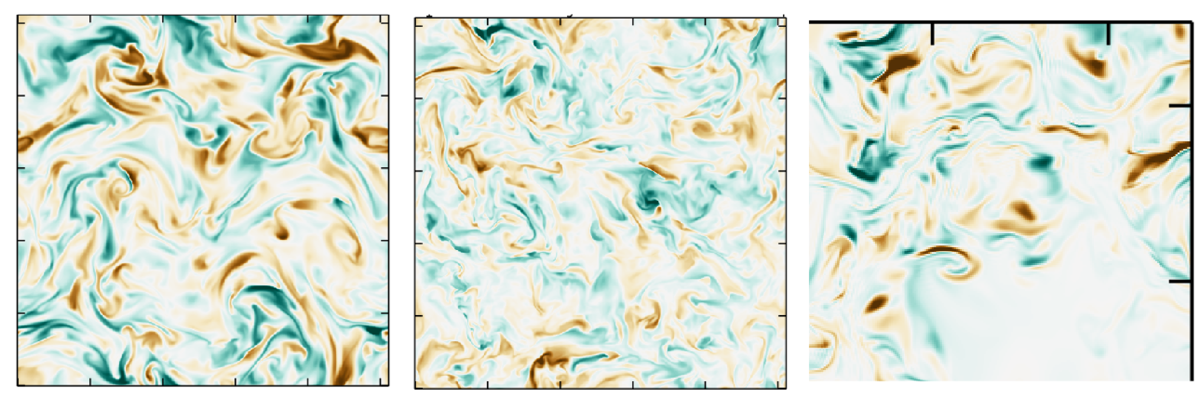
The transfer functions measure one-to-all transfers from given kinetic, q, and magnetic, k, wavenumbers. We also use shell-to-shell transfer functions which measure one-to-one transfers between each q to each k.

First Comparisons

Homogeneous (HoT) | Boussinesq Convection | MURaM

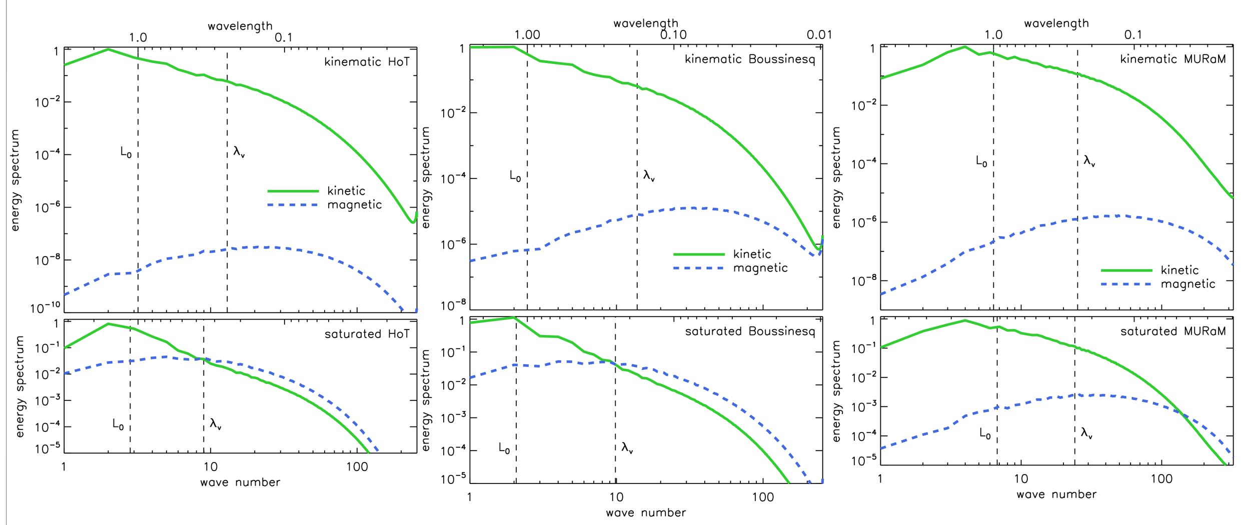


Saturated: Horizontal cuts (at average height of $\tau=1$ for MURaM) of vertical velocity field (v_z): blue for upflows, red for downflows.



Saturated: Horizontal cuts (at average height of $\tau=1$ for MURaM) of vertical magnetic field (B_z): cyan and brown for opposite polarities.

Magnetic structures look very similar for all three dynamos (the magnetic field is concentrated in the turbulent downflows for MURaM).



Kinematic (top) and saturated (bottom): Kinetic (green) and magnetic (blue dashed) energy spectra versus wavelength (in Mm for MURaM).

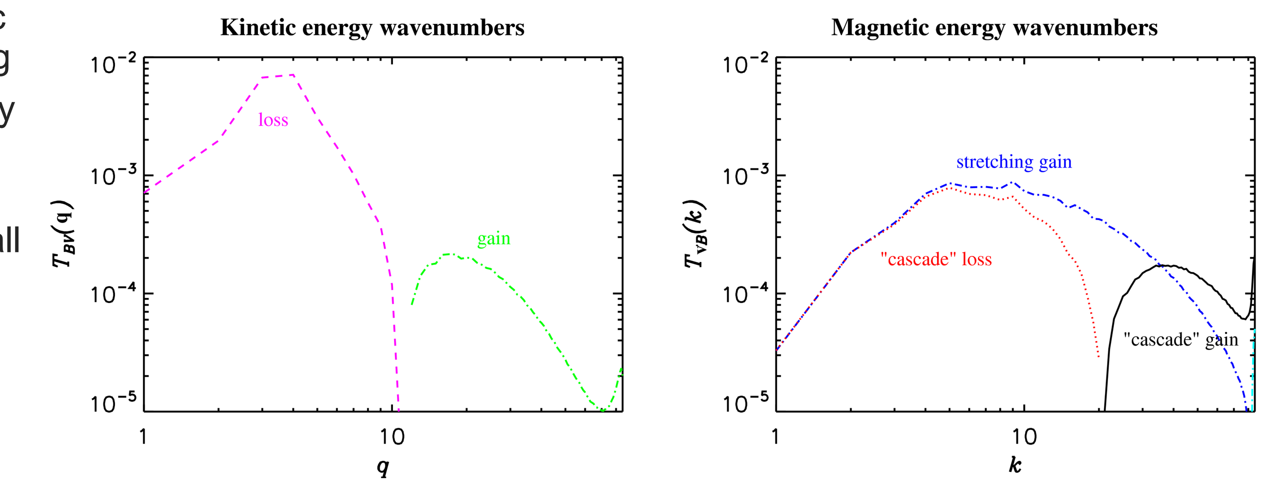
Magnetic spectra for all three dynamos are also similar. The saturated state of MURaM has a factor of 10 smaller magnetic to kinetic energy ratio due to convective losses at the bottom boundary.

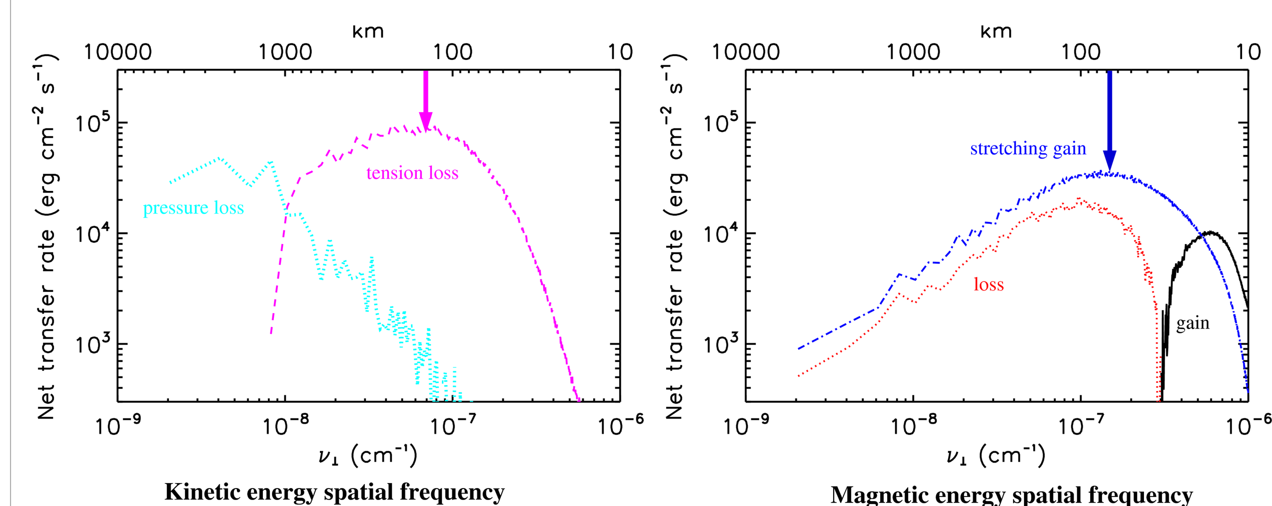
References

- Vögler et al., A&A **429**, 335 (2005).
- J. Pietarila Graham, R. Cameron, M. Schüssler, *Turbulent small-scale dynamo action in solar surface simulations*, ApJ **714**, 1606-1616 (2010); arXiv:1002.2750.
- R. Moll, J. Pietarila Graham, J. Pratt, R. H. Cameron, W.-C. Müller, and M. Schüssler, *Universality of the Small-Scale Dynamo Mechanism*, ApJ accepted 2011; arXiv:1105.0546.

Transfer functions

Transfer functions for HoT (saturated state). (Left) kinetic energy wavenumbers: $T_{BV}(q)<0$ shows energy lost working against the magnetic tension force. $T_{BV}(q)>0$ shows energy gained from the Lorentz force accelerating the fluid (saturation feedback mechanism). (Right) magnetic energy wavenumbers: net magnetic energy is gained at all wavenumbers ($T_{VB}(k)>0$) by dynamo stretching of field lines. Simultaneously, the magnetic "cascade" transports magnetic energy from smaller wavenumbers ($T_{BB}(k)<0$) to larger wavenumbers ($T_{BB}(k)>0$).

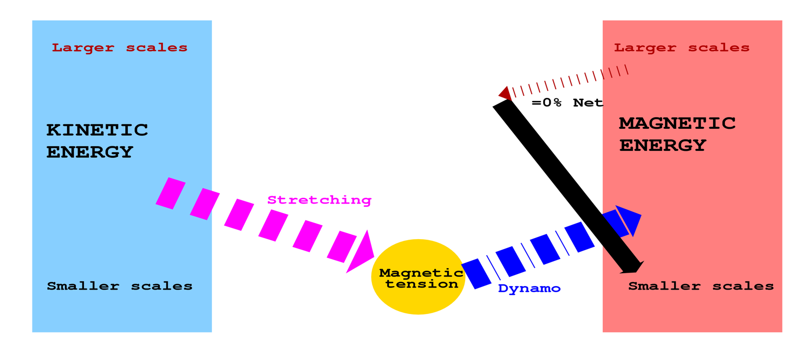




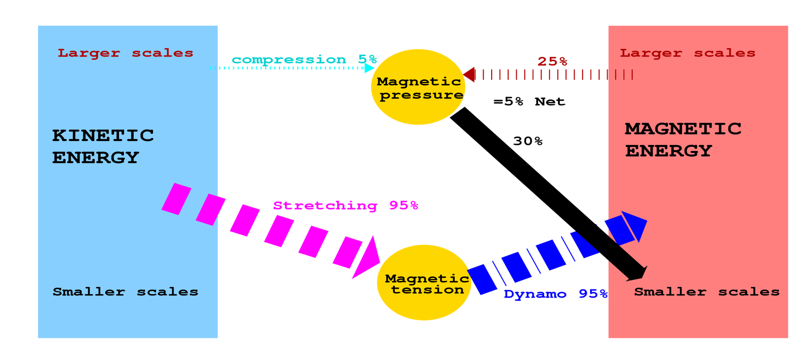
Transfer functions for MURaM (kinematic state). An additional 5% mechanism, work against magnetic pressure (Left), enhances the magnetic "cascade." The dominant spatial frequency is 1 Mm[-1]: this is convective expulsion of flux out of the granules and into the downflows.

MURaM has the same magnetic-tension stretching dynamo mechanism as HoT; inertial range fluid motions produce inertial range magnetic field (small-scale dynamo). This classical turbulent small-scale dynamo generates 95% of the magnetic field.

HoT Energy Transfers



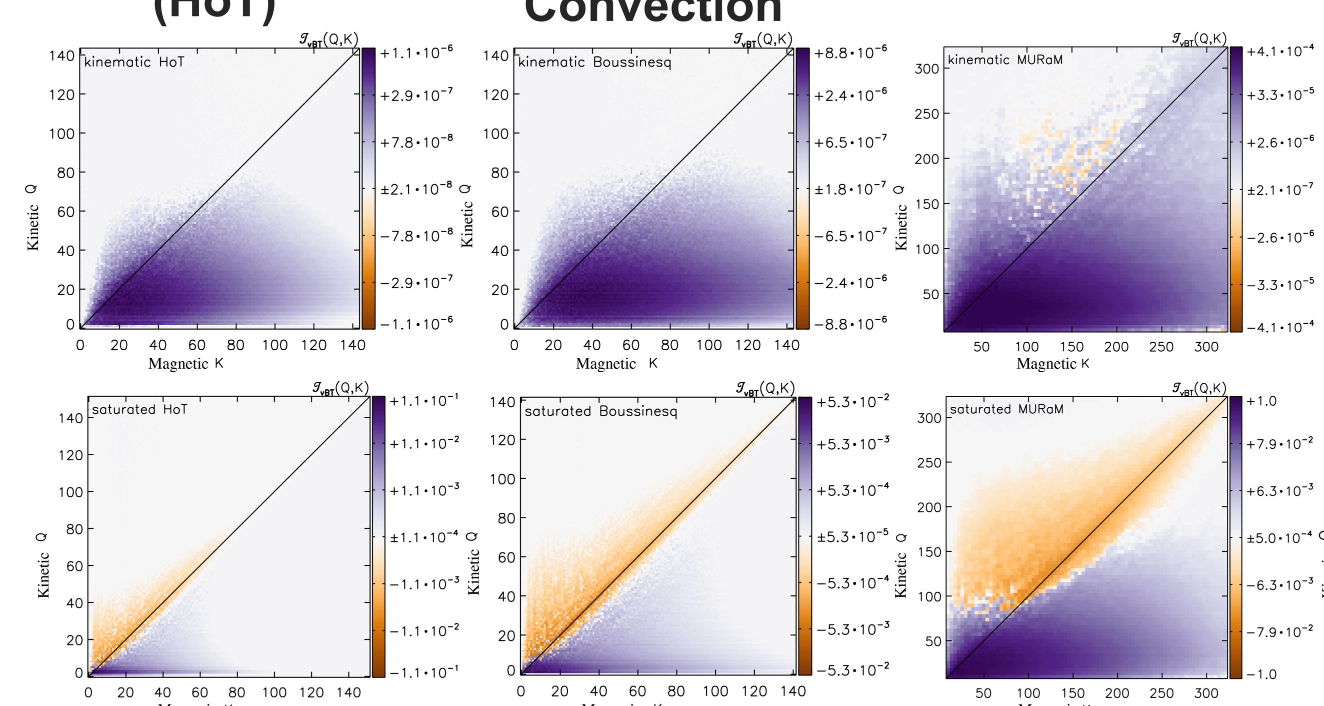
MURaM Energy Transfers



Comparison of transfer energy budgets for HoT and MURaM.

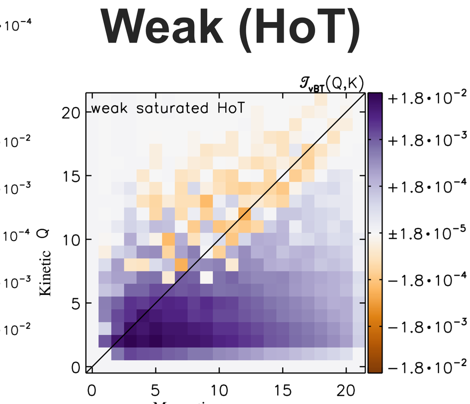
Shell-to-shell transfers

Homogeneous (HoT) | Boussinesq Convection | MURaM



Kinematic state: kinetic energy at wavenumber q works against magnetic tension force to produce magnetic energy over a wide range of larger wavenumbers k, $T_{VB}(q,k)>0$. MURaM simulation is nearer the end of kinematic state and pre-saturation feedback is visible, $T_{VB}(q,k)<0$.

Weak (HoT)



Saturated state: The saturation mechanism is seen as Lorentz-force feedback, $T_{VB}(q,k)<0$, with the magnetic field suppressing larger-wavenumber velocity fluctuations. The production of magnetic energy is also seen to shift to smaller wavenumbers, q. MURaM is more comparable to a much weaker HoT simulation (higher MURaM Reynolds numbers are needed for a stronger dynamo).

Conclusions

- 95% of the magnetic energy in MURaM is produced via magnetic tension/stretching of field lines.
- The shell-to-shell transfers are *the same for all 3 dynamos*: the small-scale dynamo mechanism does not depend on large-scale forcing, isotropy, nor on added physical effects in MURaM (universality).
- $P_M \ll 1$ dynamos have been demonstrated for HoT. MURaM has the same dynamo as HoT ⇒ the dynamo will work for MURaM (and the Sun) even at small magnetic Prandtl number. **The solar convective velocity field *is* capable of supporting classical turbulent small-scale dynamo action.**

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